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No. 527

METAL CONSTRUCTION DEVELOPMENT

By H. J. Pollard

PART II

Strip Metal Construction - Wing Spars

From Flight, March 29, and May 31, 1928

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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PART II.

Wing Spars

The reader will probably be aware that the design of parts of airplane structures built up from metal strip began to be very seriously considered late in the year 1918, when the rapidly dwindling supplies of long lengths of timber suitable for spars made it urgently necessary that these members should, if possible, be made from other materials. With the end of the war the intensive study of the possibilities ceased, but sufficient work had been done to prove that metal spars suitable for normal single-seated and two-seated airplanes could be made which would show substantial savings in weight over wooden spars of the same strength. Very efficient shallow spars, 2 to 4 inches deep, were then made and tested but the early promise of rapid development did not materialize. Sufficient data for the successful design of deeper spars were not available and the problem of making metal ribs of equal weight and stiffness compared with timber ribs was found most difficult to solve. Speaking generally,

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it is not difficult for a spar designer to produce a section from 2 to 5 inches deep, giving a stress of 60 to 70 tons per square inch, but between, say, 5 and 12 inches this result is not easy of attainment. Above 12 inches the ordinary box spar, and probably the single web spar, is scarcely practicable, and a girder arrangement is likely to prove more efficient. In particular cases, by the introduction of numerous and varied stabilizing members, exceptions could be made to the above general statements, but special cases of spar design need not at the moment concern us.

In the design office, well supplied with drawings of sections of spars and with information regarding the stresses that are developed by various kinds of loading, the task of selecting an old or designing a new spar is simple, providing no radical departures are made from previous practice.

The purpose of this article is to bring to the notice of the technician who is inexperienced in these matters, considerations which should help him to succeed in designing spars or other structural members in thin metal. An investigation of a simple concrete example brings out some of the chief points, but we will in the first instance review two important cases of the effects of stress which have been investigated mathematically.

In his treatise on "Mathematical Theory of Elasticity," Professor A. E. H. Love studies the case of a rectangular plate having sides of length 2a and 2b, and thickness 2h, secured

at the edges and acted on by edge thrust P_1 per unit length in the direction of side of length $2a$, and P_2 per unit length on the side of length $2b$.

The conditions of loading and the dimensions of the plate are shown in Figure 1.

The form of the solution is

$$w = W \sin \frac{m \pi (x + a)}{2a} \sin \frac{n \pi (y + b)}{2b} \tag{1}$$

provided that

$$\frac{1}{4} D \pi^2 \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right) = P_1 \frac{m^2}{a^2} + P_2 \frac{n^2}{b^2} \tag{2}$$

where w is the displacement of a point on the plate at (xy) from the origin

W is a constant,

m and n integers (giving the number of corrugations or "waves" parallel to the sides of the plate) and

$$D = \frac{2}{3} \frac{E h^3}{1 - \sigma^2} ;$$

this term is called by Professor Love the "flexural rigidity" of the plate.

σ is Poisson's ratio for the material of the plate.

The above equation gives the critical thrusts. For example, if $P_1 = P_2$ the critical value of P_1 and P_2 is

$$\frac{1}{4} D \pi^2 \left(\frac{1}{a^2} + \frac{1}{b^2}\right).$$

If we take the case of a box spar with a flat plate flange, then $P_2 = 0$ and $n = 1$. It is assumed that P_1 is the only force acting on the plate. Then

$$\frac{E\ h^3\ \pi^2}{6\ (1 - \sigma^2)} \left[\frac{1}{(a/m)^2} + \frac{1}{b^2}\right]^2 = P_1\ \frac{1}{(a/m)^2} \qquad (3)$$

Therefore, for minimum P_1 (at critical equilibrium) $a/m = b$ (obtained by differentiating P_1 with respect to a/m and equating to zero). Consequently,

$$\frac{E\ h^3\ \pi^2}{6\ (1 - \sigma^2)}\ \frac{4}{b^4} = \frac{P_1}{b^2}\ ,$$

or

$$P_1 = \frac{2}{3}\ \frac{E\ h^3\ \pi^2}{(1 - \sigma^2)\ b^2}\ .$$

If the stress intensity is p, then $P_1 = p\ 2\ h$,

$$p = \frac{E\ \pi^2}{3\ (1 - \sigma^2)} \left(\frac{h}{b}\right)^2 \qquad (4)$$

The second case is that of a thin tube under compressive end load. Three types of failure may occur, according to the dimensions of the strut:

(1) The well-known failure caused by the induced stress exceeding the compressive yield of the material.

(2) Failure brought about by elastic instability of the strut as a whole, causing bending of the structure line of the member.

(3) Instability of the strut wall.

(1) and (2) are fully investigated in numerous textbooks on structures or strength of materials, and no further attention need be given to them here.

It is only within comparatively recent years that the third case has received serious attention. In ordinary structural engineering the matter is of small importance, but in aircraft engineering the reverse is the case.

Mr. R. V. Southwell obtained the formula

$$p = \frac{E}{\sqrt{3}} \; \frac{t}{R} \sqrt{\frac{m^2}{m^2 - 1}} \qquad (5)$$

where p is the stress intensity at which a tubular strut would collapse through elastic instability of the walls.

E = Young's modulus,

t = wall thickness,

R = radius of tube,

and $\frac{1}{m}$ = Poisson's ratio.

From this equation a value of $\frac{R}{t} = 115$ is obtained if $p = 65$ tons per square inch.

Equations (4) and (5) are shown plotted in Figure 2.

E for steel, has been taken as 12,500 tons per square inch.

$\frac{1}{m^2} = \sigma^2$ has been taken as 0.08, for steel.

It has consistently been found that the ratios of t/R and h/B are too low, the theoretical value of t/R for tubes showing a much greater discrepancy with experiment than does the value of h/B for flat plates (Fig. 3).

For the most carefully prepared and conducted tests on the most carefully made tubes the writer would expect to find increases of at least 50 per cent in the value of t/R over the theoretical values for the same stresses.

Unfortunately, similar mathematically established formulas have not been established for complete corrugated sections, but with the following notes and the above equations as a guide, the trained technician should not experience great difficulty in inventing his own formulas for finding at what stresses the sections he designs will become elastically unstable, providing he has the opportunity of observing the behavior of actual spars under load and has also the data to enable him to compare the results of a fair number of tests. Without the opportunity of actual observation any formulas he may deduce would probably have little value.

In this summary of the factors that must have their place in the desired formulas, obviously one of the most important will be K, the radius of gyration of the section. Component curves (arcs of circles are usually taken) of the cross section must have a radius to thickness ratio proportional to the stress that is to be developed. The desired general large radius of

gyration must not be obtained by the use of extended flats. The amount that can be allowed depends on the boundary conditions, but the ratio of flat width to thickness may rarely be permitted to exceed 20. Equation (4) shows that the breadth of the section must be included, and also the thickness, as shown in equations (4) and (5). A term or terms involving the size and number of corrugations and their relative position must also be included, and a very important factor relates to the degree of fixation one portion of a section receives from an adjoining section, the numerical value of which is dependent almost entirely on experience. It is obvious then why it is inadvisable to attempt to publish formulas at the present time for general use on built-up structure members. Such formulas as have been deduced may be established mathematically at some time in the future; then that will be the occasion for publication. Failing mathematical support, it is probable that formulas for particular types of spar only will be available, the limitations of each type being strictly defined.

Empirical formulas containing terms whose values in particular cases are dependent purely on the designer's experience are scarcely suitable for publication, since the probability of misapplication by the inexperienced is too great.

It should, finally, be noted that whatever expression is derived for determining the stress at which instability sets in, it must be capable of application to a complete section or to

any portion of a section, however small, because the instability may concern a section as a whole, as, for instance, a complete spar flange or a portion of such a flange; in the latter case, for example, a portion of a flange might consist of an arc having an excessive R/t ratio at an early load, a dent or short-pitched wave might form along this part, which would subsequently develop and spread, causing the premature collapse of an otherwise perfectly stable section.

Elasticians will doubtless solve these problems in time in spite of their complexity but, as in the case of the flat plate and tube formulas, it is quite certain that the results of the mathematical investigations will need considerable modification on being brought into line with practice; hence is emphasized the need for large numbers of carefully conducted, recorded, and coordinated experiments.

Consideration of a selected few of the large number which have been carried out for the Bristol Aeroplane Company will furnish further useful information.

Figure 4 is a section of a spar used extensively in "Bristol" designs. A series of tests have been made with this spar in various gauges; the dimensions of the test spar centers are shown in Figure 5, and the ratio of end load to lateral load was $P = 24 W$, P being the thrust and W half the lateral load. In Figure 3 the relation between the stress developed and the gauge of the flange is shown.

The results of three other experiments relating to flanges numbered 6a, 6b, and 6c are shown in Figure 6, but in this case stresses developed are plotted against depth of section (see Fig. 3). As an exercise, the student of the problem should try to form an expression from the data given which, when evaluated, gives approximately the stress developed on the tests. Flange 6a was not designed for use in a spar, but for a compression rib; it was convenient, however, on one occasion to use the section in a spar. This particular spar was the bottom rear member in the metal wings of the Bristol Lucifer preliminary training airplane.

The stress in an ideally designed spar would be constant along the length and across the breadth of the section at all points, and for the material used would be the maximum permissible for the maximum loading. This state, of course, is impossible of attainment, usually load factors at points of support and points of maximum bending between supports reach the lowest permissible figure. In spars made of timber, but particularly in those made from oval tube, there is little scope for making variations in thickness of material, particularly across sections where the stress variation is generally very wide.

From Figure 7 the ease with which variations can be made with strip spars is apparent.

$$\left.\begin{array}{l} I \text{ of the section} = 1.2 \\ Z \quad '' \quad '' \quad '' \quad = 0.48 \\ A \quad '' \quad '' \quad '' \quad = 0.34 \end{array}\right\} \text{approx.}$$

Take the bending moment across this section to be 31 inch/tons. Then, assuming the web section to be adequately supported (by ribs or other means - a matter that will be briefly mentioned later), the section A should withstand the maximum stress of approximately 65 tons/square inch that would be induced. Portion B has to withstand an average stress of about 40 tons per square inch, and consequently the thickness would be much less, as shown, while the stress across the web varies from a small negative to a small positive amount, and consequently the web thickness could have a value as shown; as dimensioned this web would probably withstand a compressive stress of about 22 tons per square inch or a thrust of 1,600 pounds.

The student should work out many such examples for himself, taking different cases of bending moments, deflections, and end loads. The manufacturing side of the question should be kept in view; for instance, it would be foolish at this stage to call for strip tapering in thickness from, say, 0.018 to 0.01 inch, but longitudinal variations in metal disposition are very easily made - for example, as in the case of Figure 7. If part A were subjected to an extra compressive stress along a portion of its length, an extra lamination or laminations could readily be slipped over and secured at C and C, nor would it be necessary to secure the flanges together on their curved surfaces, securing of the flats being sufficient.

It is often convenient in the case of cantilever spars to

have a number of laminations at the root, falling off to a single thickness at the tip, thus securing a fairly even distribution of stress. (For practical purposes it is not necessary to have the shape of the outside of one lamination exactly the same as that of the inside of another, that is to say, a single set of tools will often serve for all the laminations.)

Because of the ease with which high stresses can be developed in shallow members it often happens that a good spar reckoned on a strength/weight basis can be designed which only occupies a portion of the depth of the airfoil, say, 55 or 60 per cent, and which also may have the advantage of enabling external bracing fittings to be totally enclosed in the airfoil. While this latter is very desirable it is better to obtain this by other methods than cutting down the spar depth, as the shallower the spar the greater the deflection. The sight of a wing flexing up and down when an airplane is taxying, does not inspire the pilot with confidence, even though the wing might be quite steady in the air. Full advantage should be taken of the airfoil depth, and for this reason Figure 7 was chosen as an example of a type specially suited for deep airfoils. This type of spar requires various web stiffeners, and it is the writer's opinion that development of high stresses in it is a matter of more difficulty than in the box spar type, but with the present trend of airplane design in the direction of fewer external struts, it is a type which will in the end pay for the labor

that is put into its investigation and development.

A comparison of a few current types of spar will give some information on matters of design.

In Figures 8, 9 and 10, are shown types of spars developed by Messrs. Boulton and Paul, Armstrong Whitworth, and the Bristol Aeroplane Company. The first and second are copied from the Encyclopedia Britannica. Two very special features of the Boulton and Paul spar are (1) the very neat arrangement at the riveting edges, where the 180° web bend makes the assembly of these spars previous to riveting a very simple matter, and (2) the very excellent web support. The Armstrong spar is particularly noteworthy because of the entire absence of flats, the flanges and webs being wholly curved. A special feature of the "Bristol" spars is the rather wide flat riveting edges, which enables the external fittings to be secured <u>after</u> the long box has been riveted up along its four edges, as shown in Figure 11. These fittings take the form of shallow channels secured to the spar edges after assembly, making possible a continuous process of assembly, in which holes may be punched and rivets clinched simultaneously under a gang press. Rivets are at the moment put in by hand between each stroke of the press, but the possibility of an entirely automatic assembly process in which the rivets may be fed into place mechanically are evident.

These wide flats might easily be a source of weakness in the spar, but they are kept as far from the points of maximum

stress as possible and a very substantial curl terminates the web edges.

On tests on short spars where the end load has greatly exceeded the lateral load there has been a tendency for these flats to fail before the yield point of the material has been reached; but the simple manufacturing process permitted by the design has made it worth while using a heavier gauge flange or web in the one or two isolated cases that have occurred.

The question of "developed stresses" in spars is obviously of an extremely complicated nature. Formulas deduced from the Euler Bernoulli theory are used for the simple reason that there are no others to replace them; they are, moreover, easy of application. Anyone who has seen the formation of long-pitched waves in the compression flange of a spar or seen dents developing round rivets or observed the spar visually contracting in depth or spreading in breadth must have felt that the process of multiplying the end load and deflection, dividing by the section modulus, etc., was yielding a result having little bearing on the actual stress intensity in the spar under load. It might be argued that the above process results in very approximate figures of comparison, but even in this case consideration would have to be given to the methods of loading.

The student should be on his guard against being misled by what are popularly and erroneously called "figures of merit."

A few observations on the assembly into wings of box type spars, as illustrated in Figures 8, 9, and 10 will indicate some important features which have a direct bearing on the question of stress development in these members.

Figure 12 shows a portion of a two-spar wing of a normal construction; Figure 13 shows the method of joining the ribs to the spars as used in the majority of "Bristol" metal airplanes; Figure 14 shows an alternative method not so extensively used. The first method needs no description: a single pressed abutment is secured to both riveted edges, that is, each rib is secured to the two spars by four such posts. The second method may need a little explanation: the rib is held in place by springing the toggle post from the dotted position A to position B and engagement is retained with the spars by virtue of the resilience of portions of the booms. The movable posts rotate about Y, Y in which position the projections C come into contact with the spar lips. Thus, the ribs are threaded on to the spars with the toggles in position A; the same post acts as a toggle relative to the spar webs in each case, usually the post forward of each spar is made from a single pressed abutment, which is riveted to the base of the rib boom channel. In Figure 15 details of a toggle post are shown clearly. There are two objections to the first method, one being that the continuous and complete automatic assembly of flanges and webs becomes impracticable; the second objection is that riveting of rib posts to rib flanges or booms must be carried out during

wing assembly. The latter objection is not nearly so important as is generally supposed for, given the correct appliances, the eight holes can be punched and the rivets clinched in a very short time; if, however, the assembly is carried out by hand tools (hammers, sets, etc.), the process will be long and costly. Such medieval methods can find no place in the factory properly equipped for metal airplane construction. The method of assembly as shown in Figure 14 has the great advantage of permitting rapid spar production. It cannot be said definitely at the moment that this method of wing assembly results in a saving of time in the building up of the wing as a whole. It is a question of the production of the greater number of rib pressings and the fitting of these into a rib, versus the punching of eight holes, inserting and clinching eight rivets, which latter, given the suitable equipment, can be carried out very expeditiously. The fact of the matter is that insufficient production experience has as yet been obtained with these methods to enable one to decide the matter finally.

It is evident that these rib posts actually give considerable support to the spar webs. The following is a comparison of two spars of section nearly identical with that shown in Figure 4. To the sides of one spar, rib posts as in Figure 5, were secured and the second spar had no such supports.

The constants of the sections were $I = 0.38$; $y = 1.98$; $A = 0.208$; $Z = 0.192$.

t, the thickness of the flanges and webs = 0.015 inch. The method of loading was as shown in Figure 5, and the ratio $\frac{P}{W} = 24$. The spar fitted with rib posts failed at a value of W = 435 lb., the central deflection being 1.2 inch.

In as far as a formula based on the assumption "plane sections remain plane" applies at the moment of failure, it would be true to say that the developed stress was

$$f = \frac{435 \times 1.2}{2,240 \times 0.192} \mp \frac{4.66 \times 1.2}{0.192} \mp \frac{4.66}{0.208}$$

$$= \quad 12.1 \quad + \quad 29.1 \quad + \quad 22.4$$

$$= 63.6 \text{ tons/sq. in.} \qquad (1)$$

The depth of the spar did not alter appreciably during the test.

The second spar, however, failed at a load W of 380 lb., the greatest deflection measured on the center line of the web being 1.01 in.

The spar contracted in depth at the center from 3.96 in. to 3.54 in.

The "developed stress" reckoned on the original moment of inertia was

$$\frac{380 \times 13.25}{2,240 \times 0.192} \mp \frac{9,120 \times 1.01}{2,240 \times 0.192} \mp \frac{9,120}{240 \times 0.208} =$$

$$= 11.72 + 21.4 + 19.5 = 52.62 \text{ tons per sq.in.} \qquad (2)$$

The moment of inertia of the central section of the spar at the instant preceding failure was 0.31 in.^{4} approx., the Z being

0.175 $in.^3$. The developed stress reckoned on this latter figure was therefore

$$12.85 + 23.5 + 19.5 = 55.85 \text{ tons per sq.in.} \qquad (3)$$

an increase of about 6 per cent over (2).

The need for accurate spar measurements being recorded as tests proceed, is therefore emphasized. In this particular case the fitting of rib posts resulted in an increase of "developed stress" and load supported of about 14 per cent.

In developing any new type of spar all the stresses that may be induced by the external forces and couples should be considered. Usually only the longitudinal stresses are calculated, the shearing stresses being nearly always small by comparison; this condition has been found to be true in most of the spar types so far constructed, but it does not necessarily follow that the shearing stresses can be neglected for all types. Most stress calculators have at one time or another been incited by the light appearance of a web and the existence of large lateral forces to compute the shearing stresses along the axis of a spar. The writer cannot recall a single instance of this stress having any influence on the spar dimensions. One would, for instance, never trouble to calculate this stress in the case of the box spars described in the last article, but it should not be assumed that this case could never be of any importance.

Space does not permit of a full investigation into the question of shear stresses in spars, but in the case of single web

spars similar in type to Figure 7 subjected to heavy shear loads, the maximum horizontal and vertical shear stresses can reach a very high figure if the single web is very thin. For example, in a section 4 inches deep having a single web 2 in. by 0.01 in., subjected to a shear force of 1 ton the maximum intensities, horizontal and vertical, of the shear stress would be of the order of 30 tons per square inch. In such a case the shearing stresses could not be neglected.

If it is considered expedient we will give this subject closer study in a later article.

The following are further items in the normal construction shown in Figure 4. The ribs in their most elementary form consist of upper and lower booms of channel construction bent to the airfoil shape, the aforementioned rib posts and three lengths of channel sectioned bracing per rib, one short piece in the nose, a second length between the spars, and the third portion in the tail of the rib, the outside width of the bracings and the inside width of the booms are identical. At the panel points the sides of the bracings are folded on to the base and this folded section is riveted to the base of the channel. This construction has proved satisfactory in every way, obviously it is cheap, light and strong. Failure of the ends of the bracings by fatigue has occurred, but this trouble has been overcome without much difficulty.

Several methods of securing leading and trailing edges have

been tried, but the extremely simple method shown in Figure 16 is as good as any; special tools being available for punching the holes and clinching the rivets. The use of hammers and sets must result in a costly job. The main point concerning the method here illustrated of fastening the leading edge is that the true shape of the nose of the airfoil is easily obtained. If special tools are made for more elaborate forms of attachment, for instance, as shown in Figure 17, and afterwards a radical change is made in the airfoil shape, these special tools have to be replaced at considerable cost.

We will now consider a few special cases of spar construction as developed by the Bristol Aeroplane Company. Each of these special cases refer to tapered spars. Tapered members seem to be one of the bugbears encountered in metal construction development, but it is difficult to see why this is so.

Figure 18 shows a metal spar designed for the Bristol "Brownie." The flanges consist of a main corrugated section, the outwardly extending flats of which are secured to a channel, the base of the channel being suitably lightened. The channel rib posts are secured to the sides of the boom channel as shown in Figure 19, but in this case the gusset plate is not required (see below). The special feature of the construction, however, is the shear member; this consists of a single length of tube, flattened at intervals and bent up as shown, the same rivets securing the tube, channel and flange edges. The construction

is identical in principle with the rib construction previously described. A second form of tapered spar is shown in Figure 20. No very special feature is here introduced, the bracing following ordinary girder construction of the Pratt or N type, the verticals are continued above and below the flanges and the rib booms are secured to their ends exactly as shown in Figure 19. The main booms are identical with those shown in Figure 18, but in this case the channel side alone is insufficient for securing the bracing, and gusset plates are necessary as shown in Figure 19. The type of end fitting best suited to these constructions is shown in Figure 20.

The third special feature is shown in Figure 21. The taper is obtained in this case by making the webs from flat strip, grooves being rolled along the narrowing edges, each edge being formed separately in the manner shown in Figure 22; the extended flats in the deep portions of the web require reinforcing at intervals by internal stiffeners. Spar posts of the type shown in Figure 23 lend additional stiffness, particularly if the edges of the center portion of the channel are bent outwards and riveted to the flat webs.

Other methods of tapering might be described, but the above are typical cases; there appears to be no great aerodynamic advantage in having long tapers up to the wing tips, in the case of biplanes, but the saving in weight is appreciable. By cutting the wing spars short and riveting on a tapered web at each

end as shown in Figure 24, a considerable weight reduction is possible.

For example, in a normal two-spar wing of say, 6-foot chord, a taper of 2 ft. 6 in. should result in a saving of weight of at least 1.5 lb. per spar, making an allowance for smaller ribs, a saving in weight over a wing of constant depth throughout its length of 3.5 lb. per wing tip should easily be accomplished. The weight reduction for the whole aircraft in this case would be 14 lb. Putting the argument in another way, the 2 ft. 6 in. length of tapered wing tip would be at least 40 per cent lighter than a parallel wing of similar length. A saving of this amount surely justifies some small increase in cost. For tapers much shorter than the above an ordinary round tube secured to the webs is effective and saves considerable weight.

Interplane struts built from strip show great savings in weight over solid wooden struts and to a lesser extent over streamline tube. Such a strut is shown in Figure 25. The strut consists of a steel leading edge, to the extremities of which plate end fittings are riveted. One such end fitting is shown. In general, the leading edge is of curved channel shape and to the longitudinal edges is riveted a lightened web of channel form with the sides of the channel bent inwards. The edges of the fairing are grooved in the manner shown, and this portion of the complete strut is simply pulled on from one end and is held in place simply by the pressure of the grooves.

The fairing carries no end load and can be made either from a light alloy or very thin steel, consequently suitable stiffeners are required at intervals, these being simple pressed parts. A portion of one of the stiffeners is shown near the top of the fairing. The weight of such a strut 6 ft. long under a compressive load of 2,240 lb., is 3.8 lb.; the lightest timber strut of this length and otherwise complying with the conditions would be 6.3 lb., while the best solid-drawn streamline tube would weigh 4.5 lb.

The above descriptions and illustrations by no means exhaust the possible methods of steel spar construction, but represent merely some of the designs of which the writer has had experience. Spars have been made with interlocking edges after the manner of Figure 26, the basic idea presumably being the elimination of riveting or bolting processes. Others have been made with vertically corrugated webs; this latter feature, one imagines, effectively overcomes the trouble of the decreasing of spar depth under shear loads, but it is difficult to see how such a web could carry much end load.

It may be said, however, that methods now in use are likely to be replaced by technique of design and construction far superior to that at present existing, and that at no very distant date.

For Part III, see N.A.C.A. Technical Memorandum No. 528, which follows.

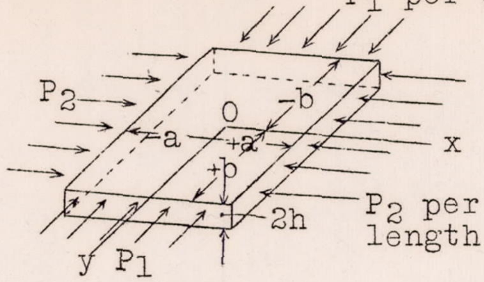
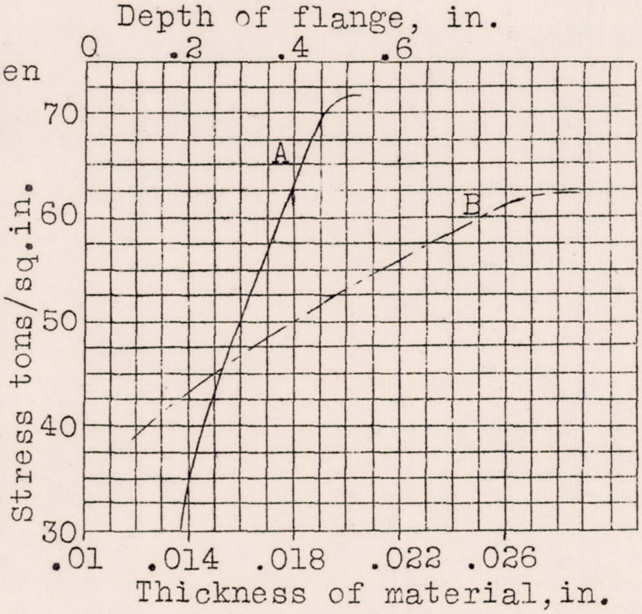


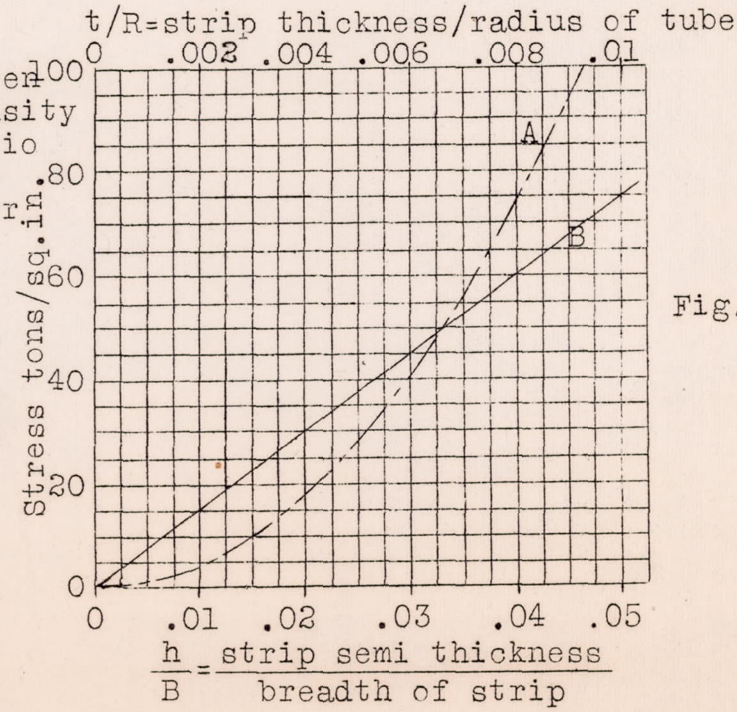
Fig.1



A, Relation between depth of spar flange and stress developed from flanges 6a,6b,6c. The gauge and other dimensions as shown on the drawing.

B, Relation between thickness of material in flange of spar Fig.4 and stress developed in section.

Fig.2



A, Relation between critical intensity of stress and ratio of semi thickness to plate width for flat plate under end load.

B, Similar ratio for tubes abscissae being wall thickness to radius ratio.

Fig.3

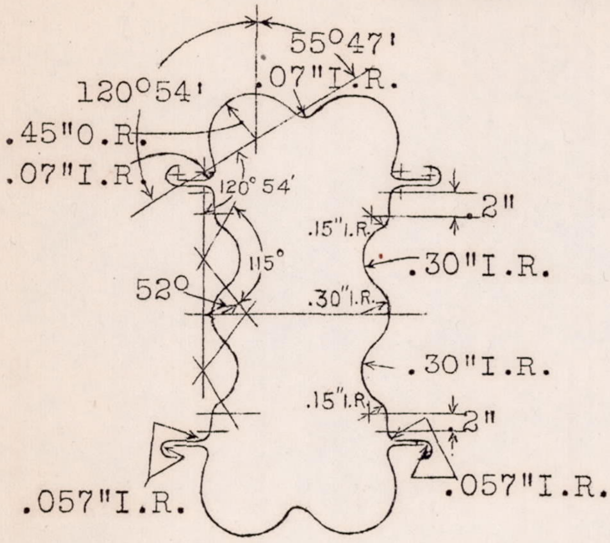


Fig.4

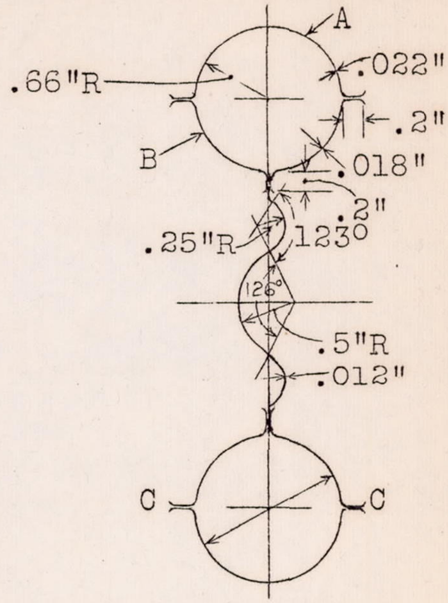


Fig.7

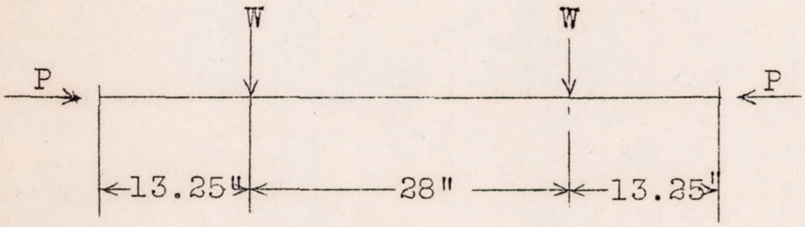
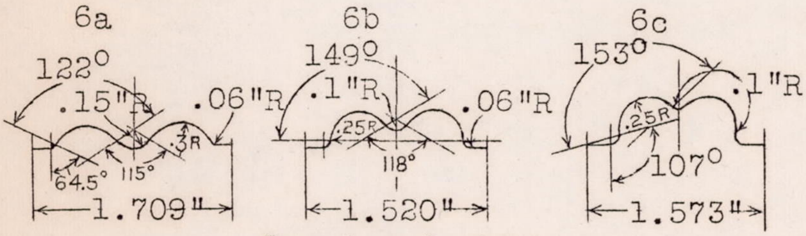


Fig.5



Developed width

2.014 1.995 2.269

Radius of gyration⊙

.0788 .1123 .1774

⊙ about axis through C.G. and parallel to flats.

Thickness of material in each case .015"

Fig.6

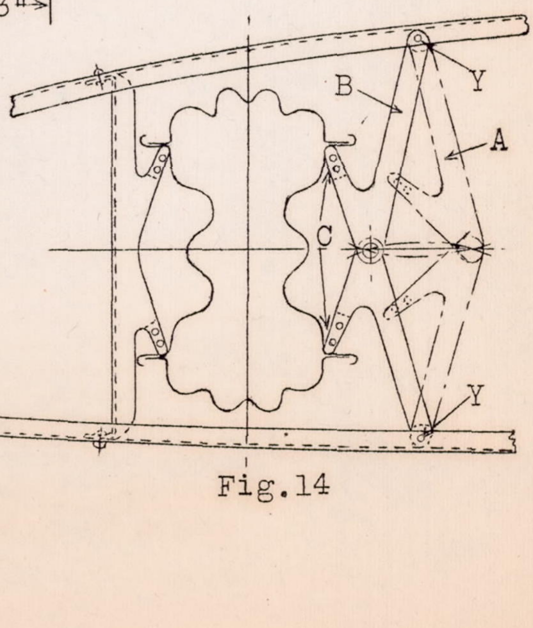


Fig.14

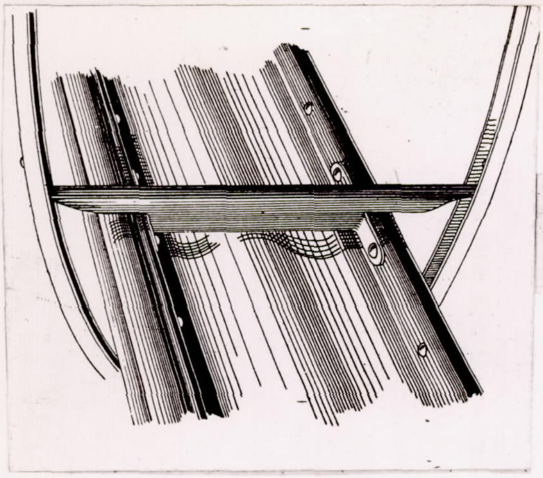


Fig.13

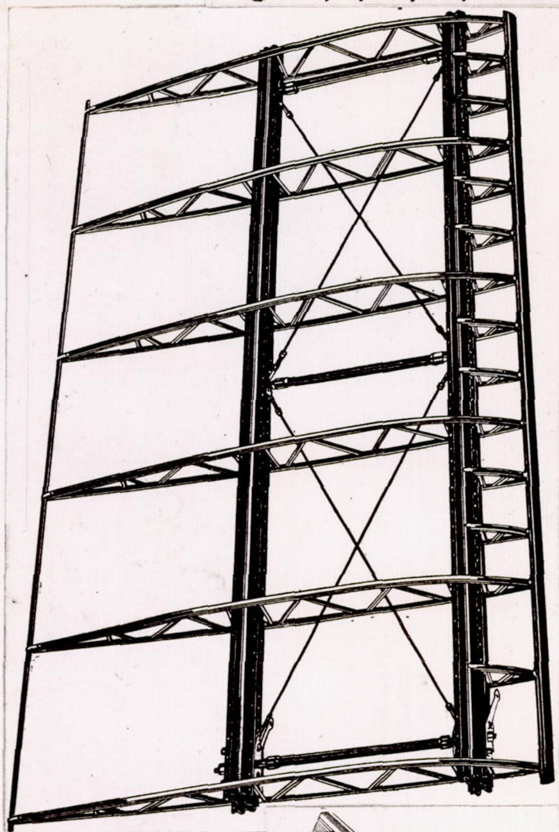


Fig.12

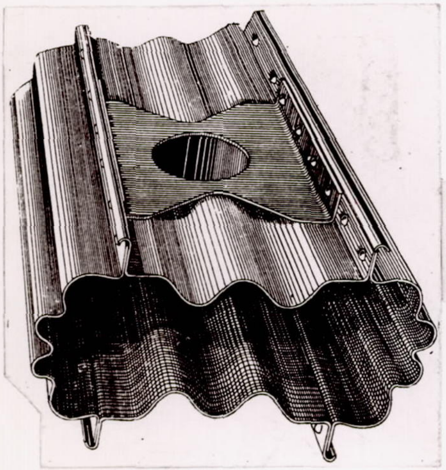


Fig.11

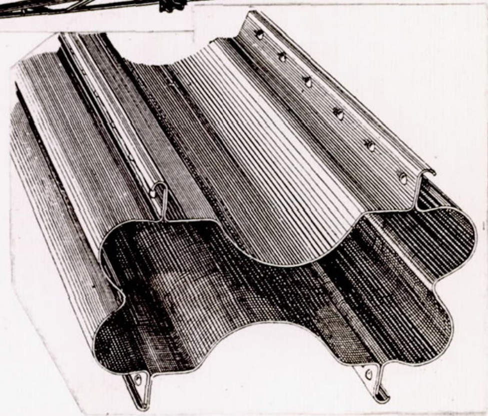


Fig.10

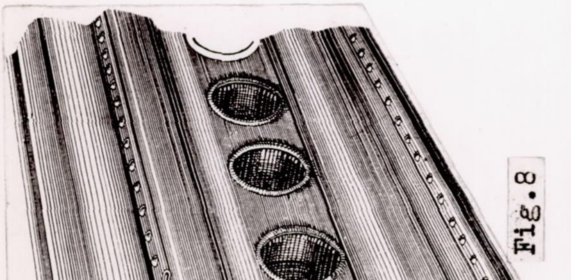


Fig.8

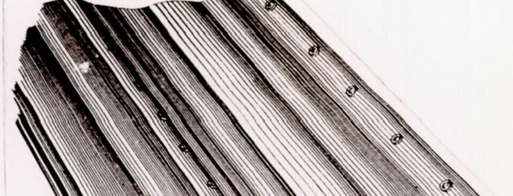


Fig.9

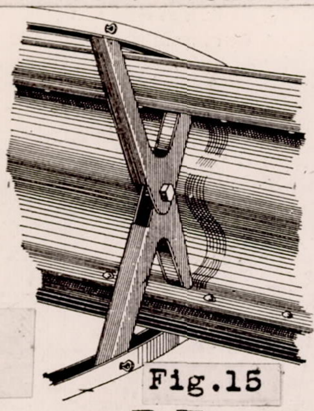


Fig.15

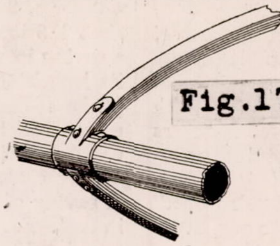


Fig.17

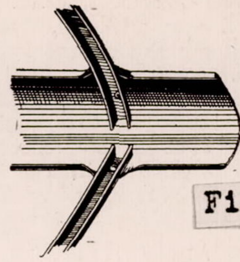


Fig.16

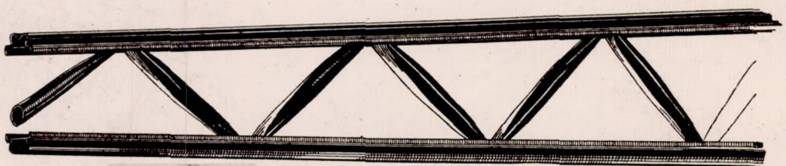


Fig.18

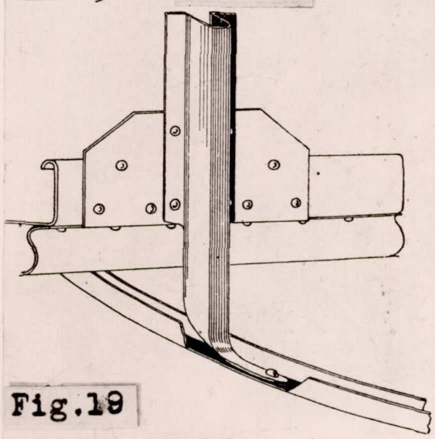


Fig.19

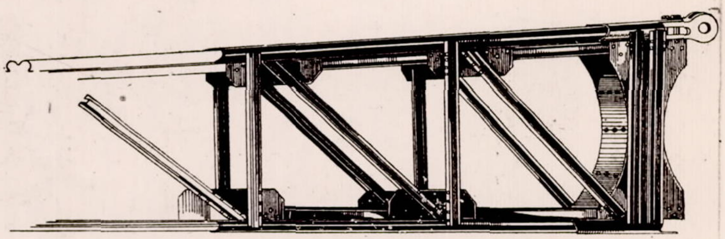


Fig.20

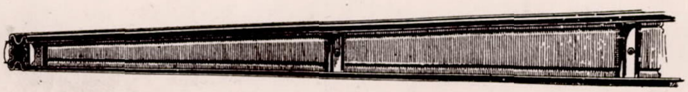


Fig.21

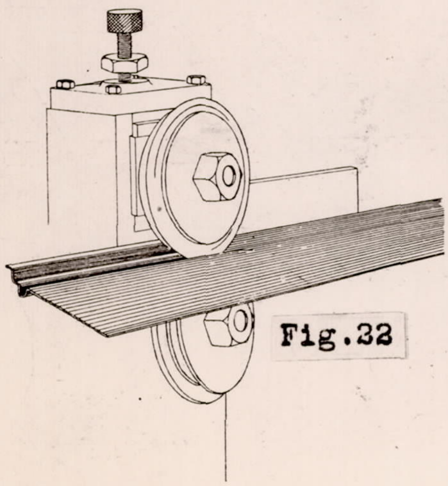


Fig.22

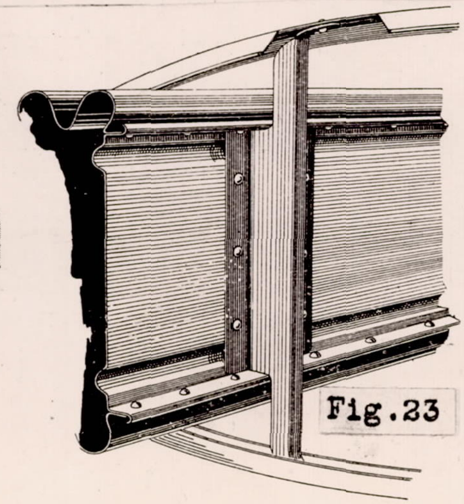


Fig.23

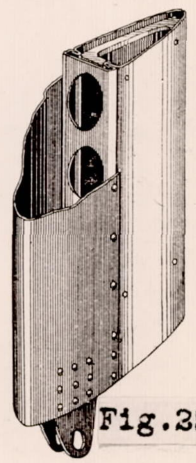


Fig.25

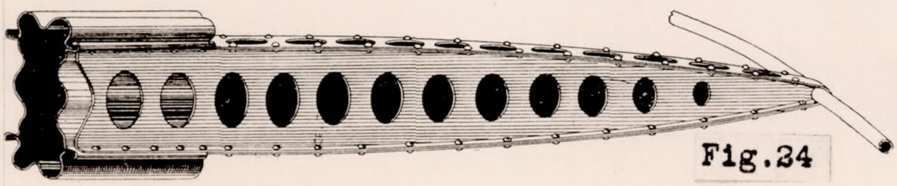


Fig.24

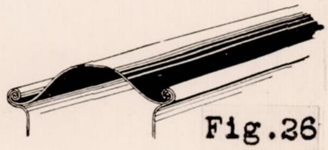


Fig.26

13134 A.S.